



# Unusual Changes in Stratospheric Ozone and Water Vapor Over Antarctica and its Relation to Mesosphere Dynamics during a Minor Sudden Stratosphere Warming

G. Venkata Chalapathi<sup>1</sup>, S. Eswaraiah<sup>2\*</sup>, P. Vishnu Prasanth<sup>3</sup>,  
Jaewook Lee<sup>2</sup>, K. Niranjan Kumar<sup>4</sup>, Yong Ha Kim<sup>2</sup>

<sup>1</sup>Department of Physics, Govt. Degree college, Anantapur-515001, India; <sup>2</sup>Department of Astronomy and Space Science, Chungnam National University, Daejeon- 305-764, Korea; <sup>3</sup>Department of Physics, Sree Vidyanikethan Engineering College, Tirupati- 517102, India; <sup>4</sup>Atmosphere and Ocean Research Institute (AORI), The University of Tokyo, Chiba, 277-8568, Japan.

## ABSTRACT

**Objective:** Usually, the stratospheric ozone will show its significance in the variability of mesospheric tides in normal days over the low-latitude region. But during sudden stratosphere warmings, the water vapor and ozone over the polar region will change and shows some different effects on mesosphere tides. In the present study, we have provided the unusual changes in both water vapor and ozone over Antarctica and their role in altering the mesospheric tides.

**Method:** Using MLS data in the stratosphere and Rothera (68oS, 68oW) MF radar observations in the mesosphere, the variability of Antarctica ozone and H<sub>2</sub>O during sudden stratospheric warming (SSW) winter 2010, and their influence on mesosphere dynamics has presented. The unusual increment of ozone reduction is noticed and consequent enhancement in H<sub>2</sub>O and HNO<sub>3</sub> is also observed during the warming period. Mesospheric tidal components (diurnal, semi-diurnal and ter-diurnal) have been estimated using the hourly wind data from the MF radar.

**Result:** The unusual changes in H<sub>2</sub>O and Ozone were observed during the warming period the similar behavior was observed in semi-diurnal tidal components during 2010 winter and their relation to ozone enhancement is discussed.

**Conclusion:** The observations indicate that the enhancement of H<sub>2</sub>O and HNO<sub>3</sub> leads to produce the ozone during warming period and hence the increment in ozone reduction is achieved over the polar region. Further, the enhancement of Brewer-Dobson mean circulation was clearly noticed through ozone transport during the warming period. The tidal enhancement after the SSW could be due to the non-linear interaction between planetary waves and tides.

**Key Words:** Sudden Stratospheric Warming, Ozone and H<sub>2</sub>O variability, Mesospheric Tides, MF Radar

## INTRODUCTION

It is well known that in the winter polar stratosphere, stratospheric sudden warming (SSW) occurs as a result of the interactions between vertically propagating planetary waves and the zonal winds (15). Ozone destruction occurs over both the polar regions in local winter-spring. In the Antarctic, essentially complete removal of lower-stratospheric ozone currently results in an ozone hole every year (14). In the winter polar lower stratosphere, low temperatures induce condensation of water vapor (H<sub>2</sub>O) and nitric acid (HNO<sub>3</sub>)

into polar stratospheric clouds (PSCs). Further, it is understood that PSCs along with cold aerosols provide surfaces for heterogeneous conversion of chlorine from longer-lived reservoir species, such as chlorine nitrate (ClONO<sub>2</sub>) and hydrogen chloride (HCl), into reactive (ozone-destroying) forms, with chlorine monoxide (ClO) predominant in daylight (20). In the Antarctic, enhanced ClO is usually present for 4-5 months (through to the end of September) (19), leading to the destruction of most of the ozone in the polar vortex between 14 and 20 km altitude.

### Corresponding Author:

Dr. Sunkara Eswaraiah, Department of Astronomy and Space Science, Chungnam National University, Daejeon, Korea; Ph:+82-10-30690508; E-mail: eswar.mst@gmail.com

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Understanding the variabilities of H<sub>2</sub>O and ozone in particular during the SSW events is important to understand the variabilities of mesospheric tides, as the forcing of the semi-diurnal tide, in particular, is mainly due to the absorption of ultraviolet radiation by ozone in the stratosphere and mesosphere. Few studies have been established on the tidal variabilities at high-latitudes in relation to the major SSW events over NH hemisphere (2,12). Such studies over SH hemisphere are sparse.

It is well established that ozone reduction takes place in the polar region especially in Antarctica region and hence ozone hole during winter. The chemistry of ozone formulation and its reduction during normal year winters and during 2010 minor SSW period is well explained by de Latt et al. (5). In their study, they identified that ozone reduction has been enhanced during the 2010 winter period. In the present study, we are going to explain how this ozone enhancement during 2010 winter will affect the tides in the MLT (Mesosphere lower thermosphere) region. Such study was not done so far, for the first time we are providing in detail study on the variability of MLT tides during the minor event occurred in 2010.

### Data

In the present study, we make use of stratospheric zonal winds and temperatures obtained from ERA-Interim reanalysis datasets provided by the European Center for Medium-range Weather Forecasts (ECMWF) (1) for the evaluation of 2010 minor SSW event. The water vapor and ozone profiles are retrieved from Microwave Limb Sounder (MLS) and mesosphere tides from Rother MF (Medium Frequency) radar.

### Methodology

The ERA-Interim reanalysis provides the data between the pressure levels 1000 and 1 hPa (~0-48 km) with a latitudinal and longitudinal grid of  $1.5^\circ \times 1.5^\circ$ . We have utilized zonal mean temperature and zonal winds at 10 hPa.

Earth Observing System (EOS) Microwave Limb Sounder, hereafter called MLS, is one of the four instruments aboard NASA's Aura satellite, and it has a radiometer that retrieves temperature from the bands near the O<sub>3</sub> spectral line at 118 and 239 GHz. It measures the temperature from 316 to 0.001 hPa pressure levels with a track resolution of 230 km, which includes the global coverage from 82 S to 82 N with ~ 15 orbits per day, providing ~30 samples daily for given latitude. Details of the MLS and temperature validation are given in Schwartz et al. (17). In the present study, we have used the H<sub>2</sub>O, HNO<sub>3</sub>, temperature, and ozone (O<sub>3</sub>) profiles derived at 80 S.

To study the mesosphere dynamics during the 2010 minor SSW period, we used a Rothera MF Radar (68 S, 68 W) wind

measurements, which is a coherent, spaced-antenna system and has been operated since 1997. The radar has a transmitting power of 25 kW at a frequency of 1.98 MHz and provides winds in the mesosphere at 4 km altitude resolution every hour (11). The hourly wind profiles during 2010 have been used in the present analysis.

## RESULTS AND DISCUSSION

### Evolution of 2010 SSW in SH

Fig. 1 depicts daily zonal mean temperature at 80 S (Fig.1a) and zonal wind at 60 S (Fig.1b) obtained from ERA-Interim reanalysis dataset for the year 2010 observed at 10 hPa. The daily mean amplitude of PW of zonal wavenumber (1) and 2 at 10 hPa over 60 S is displayed in Fig.1c. The PW amplitudes of 1 and 2 were computed from the distribution of geopotential heights along the constant latitude.

It is clear from the figure that during 2010 three episodic minor warming events occurred in early August (day 212), mid-September (day 259) and in the end of October (day 300), marked with dotted vertical lines. Though three episodic warmings occurred in 2010, September (day 259) event was the record one and influenced the mesosphere largely (6,7). During 2010 the temperature indicates that the warming lasted for more than eight days with temperature increases of ~10-15K from the normal days and the second event (day 259) was the most noticeable. The zonal wind was weakened by ~20-25 m/s in each episodic warming.

During 2010 minor SSW, the amplitude of PW (2) over 60 S was comparable to that of PW (1) during the first episodic warming (Fig.1c) and later PW (1) is stronger than PW (2). Further, the PW (1) amplitude during 2010 winter was weaker than the 2002 major SSW, and hence the PW interaction with the mean flow may lead to only deceleration, not a reversal, of zonal wind over 60 S at 10 hPa (Fig. 1b).

### Reduction in ozone destruction: 2010 SSW

Figure 2 presents the daily mean variability of HNO<sub>3</sub>, H<sub>2</sub>O and O<sub>3</sub> for the 2010 minor SSW year and also other years at different heights (~22, 32 and 68 hPa) derived from MLS measurements at 80 S. H<sub>2</sub>O is given in parts per billion (ppbv) and ozone is given in parts per million (ppmv). Further, the five-day running mean was functional in order to reduce noise if any of the data and to obtain better clarity in comparison with different years. In the figure top panel shows the HNO<sub>3</sub>, H<sub>2</sub>O variability at mid stratosphere ~22 hPa (25 km) and corresponding ozone (Figs.2(a)-2(c)), lower two panels show the similar behavior at lower stratosphere ~32 hPa (23.5 km) and ~68 hPa (19 km)). From the figure, it is clear that the reduced photochemical ozone destruction is evident in 2010 at 25 km, during mid-August and in early September.

ber when the HNO and H O are moderately increased and it could be due to an increase of stratopause temperatures during SSW. However, at lower stratosphere heights the process is continuing and following as usual winter trend and not affected by SSW and hence photochemical ozone destruction is unaffected.

Usually, during winter, a strong polar vortex forms over Antarctica and it inhibits the mixing of warm mid-latitude air and enhances radiative cooling in absence of solar radiation. The average minimum winter temperatures over Antarctica will be ~193K. If the temperature drops below ~195 K, polar stratospheric clouds (PSCs) are formed in the Antarctica ozone layer. The most common type of PSCs forms from nitric acid (HNO) and water (H O). The PSC formation will occur on an average of 1-2 months in Arctic and 5-6 months in Antarctic regions. Once formed, PSC particles will undergo vertical transport to lower altitudes due to gravity, they trigger the chemical reactions (denitrification and dehydration) in the stratosphere and cause the highly reactive chlorine gas (ClO) to be formed, which catalytically destroys ozone. As long as temperatures remain sufficiently low, PSC formation will continue and hence the ozone destruction. However, once the sunlight increase due to season transition vortex warms, the PSC will disappear slowly and halogen species are deactivated and hence the ozone reproduction starts. Both H O and HNO in the stratosphere will affect directly or indirectly on ClO production in PSC reaction and reduce the amount of ClO production and hence reduce the ozone destruction.

The clear mechanism for the reduction of photochemical ozone destruction at 22 hPa is shown in Fig. 3. The figure depicts five-day running mean MLS measurements of HNO, O, H O and temperature as a function of time for the 2010 minor SSW year and other non-SSW years 2012, 2013 at 22 hPa (~25 km), where the ozone reproduction is greater due to SSW effect compared to other lower altitudes. Once temperatures drop below the PSC formation temperature around the day 150 (~1 June), denitrification starts as evidenced by the decrease in HNO<sub>3</sub>. However, full denitrification will be reached within about 20 days. At the same time, the chlorine reservoir HCl is empty (18) due to chemical reactions of HCl on PSC's. Usually, dehydration starts about 20 days later than denitrification as the pure ice formation temperatures are delayed by 20 days after PSC formation temperature. Due to decrease of solar isolation in August (~day 225) ozone is being destroyed slowly by halogens as ClO start to increase around day 225. When ClO is abundant around day's 250-270 (mid-September), ozone destruction is maximum. During late winter /transition period starts (~day 270), temperatures increases to above the PSC formation threshold level, PSCs starts to evaporate and the active halogens are rapidly deactivated back into reservoir species like HCl. The slow increase in HNO and H O starting around DOY 270 also shows that mixing is taking place. However, after

day 300 (~late October – early November) ozone slowly increases again, mainly by mixing of

mid-latitude air. This behavior is very similar for all years but different in SSW years (2010). In contrast, during 2010 SSW, the warming occurred during late August (day 212) and mid-September (259) and lasted for about a week and significantly affected the mesosphere and thermosphere (6). However, in 2010 the chemical species and ozone are greatly affected by the warmings that occurred in the stratosphere. For instance, during 2010 winter the first warming was noticed on the day 212 and the temperature was increased, even crossed the PSC threshold level and hence HNO and H O suddenly raised and ClO decreases which result in an increase of HCl on the day 212. The net photochemical chemical reactions result in increasing ozone around the day 250, instead of reduction; showing that catalytic ozone depletion at 22 hPa in 2010 is not unusual. In the following subsections, we will discuss, how these ozone increase around the days 250-270 affects the MLT dynamics.

### Sudden Stratospheric Warming-Ozone effects on the mesospheric tides

Fig. 4 depicts the daily variability of zonal diurnal, semi-diurnal and ter-diurnal tides measured by Rothera MF radar during SH winter at 80 km. Fig. 4(a) shows the variability of tides in 2010 SSW year. Fig. 4(b) shows the variability of stratospheric ozone during 2010 SSW year and non-SSW years 2012, 2013, respectively. It is clear from the figure that the semi-diurnal tidal amplitude is increasing (~40 m/s) during last 15 days of the October (day 285-300). Usually, the tidal amplitudes are falling below 20 m/s in SH winter. The role of stratospheric ozone in coupling the low-latitude stratosphere and MLT region has been studied by Goncharenko, et al. (10). They suggested that the increase in the ozone density at 2 hPa (~43.5 km) lasts ~35 days following the SSW long after the downfall of PWs, causing enhancement in SDT amplitude. However, at the polar latitudes, the mechanism is different. The meridional circulation forced by PWs in the polar region during SSW leads to transport of ozone from pole to equator (9,16), and thus increases the peak ozone heating rate at ~43 km at low-latitudes, resulting in the amplification of SDT in the MLT region (10,13).

As shown in Fig. 4b, the ozone density at 22 hPa (the ozone is usually generated at this altitude) is gradually increasing in the winter from the day 200 onwards and attains maximum value during warming day (259) and after that it extremely deviates from the normal seasonal trend, except a small hike around the day 300. The variation in ozone trend in 2010 winter could be due to the strong B-D circulation forced by enriched PWs at polar region. The circulation transported the ozone from SH to NH high latitudes as a consequence of pole-pole circulation (Figure 1 of Butchart, 2014) or it could be transported to low latitudes. Alternatively, the ozone could



be downward transported to lower altitudes in SH itself. The small upturn in the O density around the day 300 could be due to the minor warming that occurred on the day 300 (6). Since MLS satellite is located in a Sun-synchronous orbit, the zonal mean values of O might have been aliased with the migrating tides. Figure 5 indicates that even when ozone density is lower than the usual value, the SDTs are enhanced during the days 270-310. This may suggest that ozone alone may not play a dominant role in the amplification of tides over the Antarctic MLT region.

Further, we also verified the O anomaly during 2010 SSW winter and 2012 non-SSW winter periods and presented in Figure 5. It is clear from the figure (Fig.5a) that the ozone density is high at tropical region at starting of winter at 43 km (2 hPa), where the tides will generate and as soon as reaching peak warming day, the ozone is transported towards NH high-latitude region and more ozone is ascertained at 60 N, it could be due to B-D circulation at the stratosphere (Butchart, 2014, Figure 1). The B-D circulation at the stratosphere (~43 km) shown with a curved arrow in Fig.5(a) and the ozone density is comparatively low at ~60 S. In a normal year (Non-SSW) (Fig.5(b)) the circulation was not observed, and the usual trend was apparent at 43 km. It states that the strong mean circulation forced by enriched PWs at polar region, transported the ozone from SH to NH high latitudes as a consequence of pole-pole circulation (Butchart,2014) or it could be downward transported to lower altitudes at SH itself.

So, we may conclude that the enhancement of SDT amplitudes at high-latitudes are due to different effect than those observed at low latitudes (4,8,21). It tells that, the effect of ozone and water vapor is less significant on the Antarctic mesospheric tides. Thus, the above discussion suggests that the enhancement in SDT amplitudes could be due to the PWs-tidal interaction.

## CONCLUSIONS

In the present communication, we described the variability of Antarctica ozone and HO during the winter period of 2010 SSW year, and their influence on mesospheric tides. The tidal components (diurnal, semi-diurnal and ter-diurnal) in the MLT region have been estimated using the hourly wind data from both Rothera (68 S, 68 W) MF radar. The main findings are summarized as follows;

1. In 2010, we noticed record minor stratosphere warming (SSW) in mid-September (day 259) using ERA-interim data analysis.
2. It is noticed that the stratosphere chemistry below 50hPa is not affected by SSW. The chemical species ClO, HO, HNO plays a key role in destruction (ClO)

and reconstruction (HO, HNO) of ozone in the middle and upper stratosphere.

3. Though the SSW occurs during the days 250-270, the Ozone will not rise due to ozone destruction element ClO element is abundant even when HO, HNO slowly increasing (Fig.3). During the days 270-300 the ClO is falling rapidly and HO and HNO increase shows the vertical mixing and produces more ozone.
4. The unusual behavior was observed in semi-diurnal tidal components during SSW year 2010. The Semi-diurnal tidal enhancement is noticed during the days 270-310, irrespective of the day of peak warming occurred in 2010.
5. The reason why tidal amplitudes are enhancing during the days 270-300, may be explained like this: Since the ozone destruction between 20-25 km is reduced to 60% during SSW years compared to other years and the recovery of ozone is fast between the days 270-300 due to downward transport of chemical species, rather than horizontal mixing, and transport of humid rich air (HO) and hence change in vertical propagating tides. However, the effect could be low since the ozone density is less during the days 270-300.

The above discussion suggests that though the ozone destruction is reduced during SSW period, ozone alone cannot affect the tidal enhancement, it may be due to planetary wave (PW)-tidal interaction. To quantify this, issue the non-linear interaction between tides-and PWs should be discussed.

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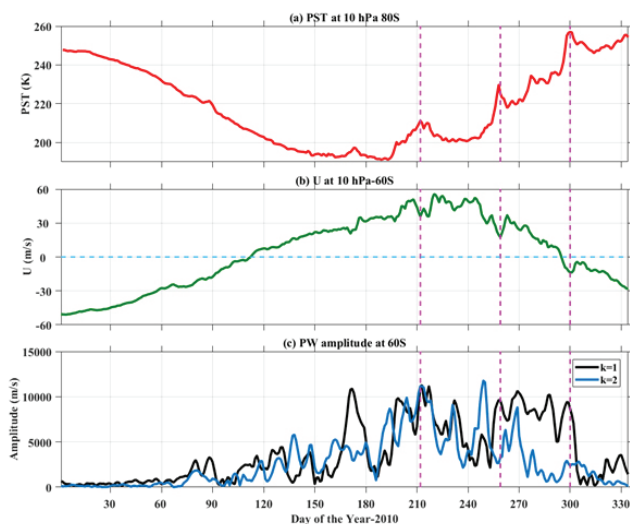
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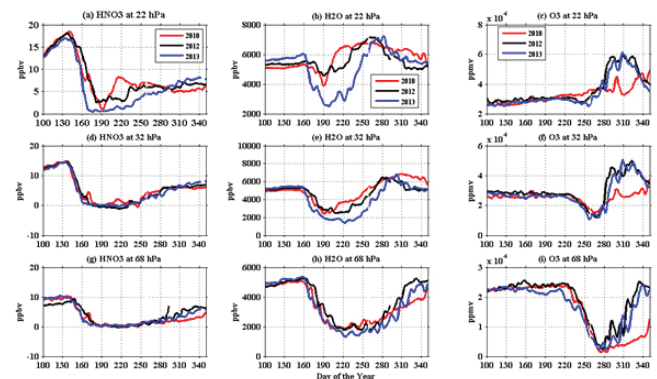
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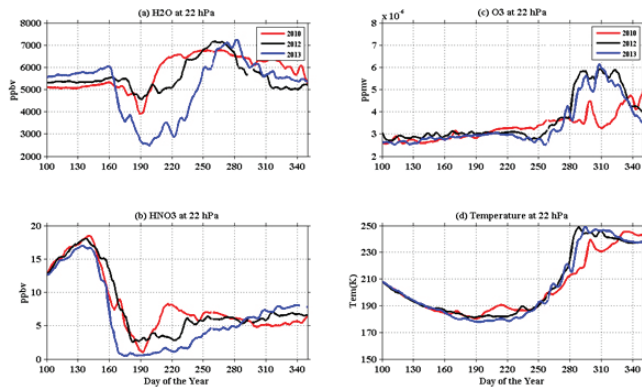
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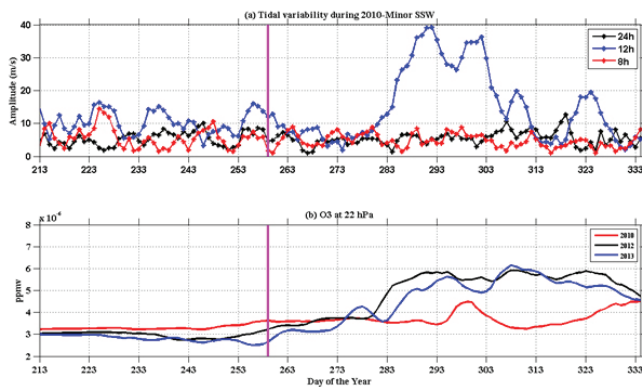
**Figure 1:** (a) Daily variation of zonal mean Polar Stratospheric Temperature (PST) at 10 hPa over 80 S. (b) Daily variation of zonal mean zonal wind at 10 hPa over 60 S during 2010 minor SSW. (c) Planetary wave amplitude of zonal wavenumbers 1 and 2 at 10 hPa over 60 S. The dashed horizontal line in (b) indicates zero wind line and the dashed vertical line indicates the warming periods in 2010.



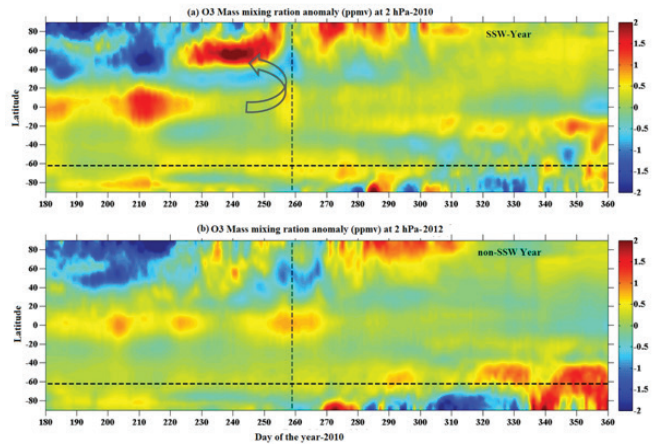
**Figure 2:** Daily mean variability of HNO, H<sub>2</sub>O and Ozone (O) in the stratosphere using MLS measurements during normal years (2012, 2013) and comparison with minor warming event year (2010) at 22 hPa (a–c), at 32 hPa (d–f), and at 68 hPa (g–i). All profiles are at ~80 S.



**Figure 3:** The five-day running mean MLS measurements of H<sub>2</sub>O, HNO<sub>3</sub>, O<sub>3</sub> and temperature at ~22hPa for the years 2010,2012 and 2013 during DOY 100-350. All profiles are at ~80 S.



**Figure 4:** (a)Variability of diurnal, semi-diurnal and ter-diurnal zonal components measured by Rothera MF radar (68 S,68 W) during 2010 SH winter at 80 km, (b) daily mean variability of Ozone (O<sub>3</sub>) in stratosphere using MLS measurements during Non-SSW years (2012,2013) and comparison with minor warming event years (2010) at 22 hPa. All profiles are at ~80 S. Vertical lines indicate the day of peak warming.



**Figure 5:** Zonal mean ozone mass mixing ratio anomaly (ppmv) profiles calculated from the south pole to north pole at 2 hPa (~43 km) altitude for the SSW year 2010 (Top Panel) and the non-SSW year 2012 (bottom panel). The vertical line indicates the day of peak warming. The horizontal line indicates 60 latitude. Curved arrow in top panel shows the transport of ozone due to mean circulation.